

# Effects of binary stellar populations on direct collapse black hole formation

Bhaskar Agarwal<sup>1\*</sup>, Fergus Cullen<sup>2</sup>, Sadegh Khochfar<sup>2</sup>, Ralf Klessen<sup>1</sup>,  
Simon Glover<sup>1</sup>, Jarrett Johnson<sup>3</sup>

<sup>1</sup> *Universität Heidelberg, Zentrum für Astronomie, Institut für Theoretische Astrophysik, Albert-Ueberle-Straße 2, 69120 Heidelberg, Germany*

<sup>2</sup> *Institute for Astronomy, University of Edinburgh, Royal Observatory, Edinburgh, EH9 3HJ*

<sup>3</sup> *X Theoretical Division, Los Alamos National Laboratory, Los Alamos, NM 87545, USA*

00 Jun 2014

## ABSTRACT

The critical Lyman–Werner flux required for direct collapse blackholes (DCBH) formation, or  $J_{\text{crit}}$ , depends on the shape of the irradiating spectral energy distribution (SED). The SEDs employed thus far have been representative of realistic single stellar populations. We study the effect of binary stellar populations on the formation of DCBH, as a result of their contribution to the Lyman–Werner radiation field. Although binary populations with ages  $> 10$  Myr yield a larger LW photon output, we find that the corresponding values of  $J_{\text{crit}}$  can be up to 100 times higher than single stellar populations. We attribute this to the shape of the binary SEDs as they produce a sub-critical rate of  $\text{H}^-$  photodetaching 0.76 eV photons as compared to single stellar populations, reaffirming the role that  $\text{H}^-$  plays in DCBH formation. This further corroborates the idea that DCBH formation is better understood in terms of a critical region in the  $\text{H}_2$ – $\text{H}^-$  photo-destruction rate parameter space, rather than a single value of LW flux.

**Key words:** quasars: general, supermassive black holes – cosmology: darkages, reionization, firststars – galaxies: high-redshift

## 1 INTRODUCTION

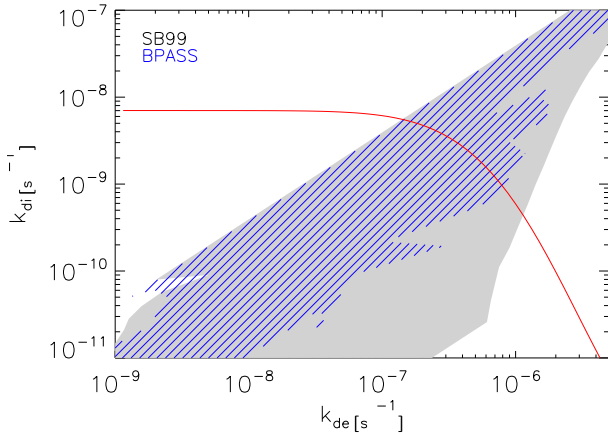
Direct collapse black holes (DCBH) have gathered much attention recently (Dijkstra et al. 2014; Ferrara et al. 2014; Chon et al. 2016; Agarwal et al. 2012, 2014; Habouzit et al. 2016) as a plausible solution to the problem of forming billion solar mass black holes very early in cosmic history as is required to explain the existence of very luminous quasars at redshifts  $z > 6$ . Pristine gas in an atomic cooling halo exposed to a critical level of Lyman–Werner (LW) radiation can rid itself of molecular hydrogen (cooling threshold  $\sim 200$  K), thereby collapsing isothermally in the presence of atomic hydrogen (cooling threshold  $\sim 8000$  K). This leads to a Jeans mass threshold of  $10^6 M_\odot$  at  $n \sim 10^3 \text{ cm}^{-3}$ , thereby allowing the entire gas mass in the halo<sup>1</sup> to undergo runaway collapse eventually forming a  $10^{4-5} M_\odot$  black hole in one go (Omukai 2001). The collapse must withstand fragmentation into Population III (Pop III) stars, which requires the gas to get rid of its angular momen-

tum via bars–within–bars instabilities (Begelman et al. 2006), low-spin disks (e.g. Bromm & Loeb 2003; Koushiappas et al. 2004; Regan & Haehnelt 2009; Lodato & Natarajan 2006) or high inflow rates in turbulent medium (Volonteri & Rees 2005; Latif et al. 2013; Schleicher et al. 2013; Van Borm & Spaans 2013).

In order for this mechanism to work, initially there must be a LW radiation field strong enough to delay Pop III star formation in a minihalo,  $2000 < T_{\text{vir}} \leq 10^4$  K, till it reaches the atomic cooling limit of  $T_{\text{vir}} \geq 10^4$  K (Machacek et al. 2001; O’Shea & Norman 2008; Agarwal et al. 2012, 2014). At this point, the flux of LW radiation illuminating the halo from nearby external stellar source(s) must be higher than a critical value  $J_{\text{crit}}$  (conventionally written in units of  $10^{-21} \text{ erg/s/cm}^2/\text{sr/Hz}$ ) to facilitate isothermal collapse of the pristine gas at 8000 K into a DCBH. Many previous studies of DCBH formation have adopted highly simplified prescriptions for the spectrum of this external radiation field, approximating the spectrum of a source dominated by Pop III stars as a  $T = 10^5$  K black body, and of a source dominated by Population II (Pop II) stars as a  $T = 10^4$  K black body (Omukai 2001; Shang et al. 2010; Wolcott-Green & Haiman 2012). However, recent studies have emphasised the need for using more realistic spectral energy distributions (SED) for these sources as the value of  $J_{\text{crit}}$  depends on the shape of the irradiating source’s SED

\* E-mail: bhaskar.agarwal@uni-heidelberg.de

<sup>1</sup> An atomic cooling halo, i.e.  $T_{\text{vir}} = 10^4$  K corresponds to a  $M_{\text{DM}} \approx 10^7 M_\odot$  at  $z \approx 10$ . If we assume that the baryon fraction in this halo is the same as the cosmological mean value, i.e.  $f_b \approx 0.16$ , then the baryonic mass of such a halo will be at least  $10^6 M_\odot$



**Figure 1.** The solid red curve is criterion for direct collapse derived described in A16, given by Eq. 3. The grey shaded region shows the range of  $k_{de}$  and  $k_{di}$  derived from SB99 stellar populations, while the blue region is the range derived from BPASS for a range of stellar populations described in Tab. 1

(Sugimura et al. 2014; Agarwal & Khochfar 2015; Agarwal et al. 2016, , A16 hereafter). These studies employed single stellar populations to represent the SEDs of Pop II stars, generating them using publicly available single stellar synthesis codes such as STARBURST99 (Leitherer et al. 1999), YGGDRASIL (Zackrisson et al. 2011) and Bruzual & Charlot (2003) model. However, in reality it is likely that a significant number of the stars will be part of binary systems. Stellar populations with significant binary fractions have higher hydrogen ionising photon yields than single stellar populations (e.g. Stanway et al. 2016; Ma et al. 2016), and so it is plausible that accounting for their existence will lead to significant differences in the value of  $J_{crit}$  that we derive.

## 2 METHODOLOGY

We apply the framework described in A16 to SEDs generated with the stellar population synthesis code ‘Binary Population and Spectral Synthesis’ (Stanway et al. 2016; Eldridge & Stanway 2016) in its second version, BPASSv2. This is done to assess the impact of binaries on the critical LW radiation field strength required to suppress  $H_2$  formation and enable direct collapse black hole formation. The unique feature of the BPASSv2 models is the inclusion of massive binary star evolution which, in the context of this work, has the effect of boosting the LW photon flux at older stellar ages (see Section. 3).

We have been motivated to consider the effects of binary star evolution by observations of local HII regions which have indicated that  $\gtrsim 70\%$  of massive stars undergo a binary interaction in their lifetimes (e.g. Sana et al. 2012). Furthermore, it has been reported recently that the BPASSv2 models are better able to account for (i) the observed shape of the FUV continuum and (ii) UV + optical emission line ratios of star forming galaxies at  $z \simeq 2 - 3$  (Steidel et al. 2016; Strom et al. 2016), as well as the properties of massive star clusters in local galaxies (Wofford et al. 2016) and Pop III stars (Clark et al. 2011; Greif et al. 2012; Stacy & Bromm 2013). Given this context, it is useful to know how the presence of massive binary stars in stellar population will affect direct collapse black hole formation. Briefly, in the BPASSv2 models, the main consequence of close binary interactions is the removal of the

**Table 1.** Summary of the stellar populations considered in this study, BPASSv2 and SB99.

Instantaneous Burst	Stellar Mass ( $M_\odot$ )	Age (yr)	Metallicity ( $Z_\odot$ )	IMF <sup>[b]</sup>
BPASSv2	$10^5 - 10$	$10^6 - 9$ yr	0.05	Kroupa
SB99	$10^5 - 10$	$10^6 - 9$ yr	0.02	Kroupa

<sup>b</sup> IMF of the form  $\Psi(M_*) = M_*^{-\alpha}$  where  $\alpha \sim 1.3$  for  $0.1 \leq M_* < 0.5$  and  $\alpha \sim 2.35$  for  $0.5 \leq M_* \leq 100 M_\odot$

hydrogen envelope in primary stars, part of which accretes onto the companion secondary star resulting in its rejuvenation (e.g. de Mink et al. 2013; Podsiadlowski et al. 1992). The resulting effect on a stellar population containing a significant binary fraction is more hot-helium and Wolf-Rayet stars in the primary population, and an effective increase in the main sequence lifetimes of secondary stars.

The mass transfer is also accompanied by angular momentum transfer, which causes stars to spin-up and results in a rotational mixing of layers allowing hydrogen to burn more efficiently; this effect, known as quasi-homogeneous evolution (QHE), is particularly strong at low metallicities (see Eldridge & Stanway 2016; Stanway et al. 2016). The most relevant consequence of these differences on the DCBH formation scenario is that compared to single star models, the BPASSv2 binary models extend the time period over which a stellar population can emit UV photons in the LW band.

The SED grid explored in this study is described in Tab. 1. It is compared to the SB99 case, which we have discussed in detail in the Appendix of A16. For the BPASSv2 models we have assumed the instantaneous burst models with ages ranging from  $10^6 - 9$  yr and a metallicity of  $0.05 Z_\odot$ . In order to understand the effect of these SEDs on DCBH formation, we make the following assumptions:

(i) The SEDs represent a galaxy of a certain age and stellar mass in a halo.

(ii) The DCBH formation region (in a pristine atomic cooling halo) is external to the galaxy, at an assumed separation of 5, 12, 20 physical kpc (Agarwal et al. 2014).

(iii) We parametrise the critical LW radiation requirement for DCBH formation in terms of the rate of photodissociation of molecular hydrogen  $k_{di}$  ( $s^{-1}$ ), and rate of photodetachment of  $H^-$ ,  $k_{de}$  ( $s^{-1}$ ) where

$$k_{de} = \kappa_{de} \alpha J_{LW} \quad (1)$$

$$k_{di} = \kappa_{di} \beta J_{LW} \quad (2)$$

Here  $\alpha$  and  $\beta$  are rate parameters that depend on the shape of the SED (Omukai 2001; Agarwal & Khochfar 2015; A16),  $\kappa_{de} = 10^{-10} s^{-1}$  and  $\kappa_{di} = 10^{-12} s^{-1}$  are normalisation constants (Agarwal & Khochfar 2015), and  $J_{LW}$  is the mean specific intensity of the Lyman-Werner radiation field at 13.6 eV. The latter depends on the choice of stellar population and the assumed separation between the galaxy and the atomic cooling halo.

(iv) In A16 we showed that in our simple one-zone model of the thermal evolution of gas in the atomic cooling halo, DCBH formation occurs when the  $H_2$  photodissociation rate exceeds a value given approximately by

$$k_{\text{di}} \geq 10^{A \exp(\frac{-z^2}{2}) + D} \text{ (s}^{-1}\text{)}, \quad (3)$$

where  $z = \frac{\log_{10}(k_{\text{de}}) - B}{C}$  and  $A = -3.864$ ,  $B = -4.763$ ,  $C = 0.773$ , and  $D = -8.154$ , for  $k_{\text{de}} < 10^{-5} \text{ s}^{-1}$ .

By computing  $k_{\text{di}}$  and  $k_{\text{de}}$  for each different SED in our two grids of models and each different separation, we can therefore determine which combinations result in DCBH formation in the target atomic cooling halo and which do not. As an example, we show in Figure 1 the full range of values of  $k_{\text{de}}$  and  $k_{\text{di}}$  we obtain with the SB99 SED grid (gray shaded region) and the BPASS SED grid (blue shaded region) for a halo-galaxy separation of 5 kpc. We see that for many combinations of stellar mass and stellar age, the LW flux reaching the atomic cooling halo is insufficient to enable DCBH formation, but that there are combinations of parameters that do yield a sufficiently large  $k_{\text{di}}$  (Eq. 3).

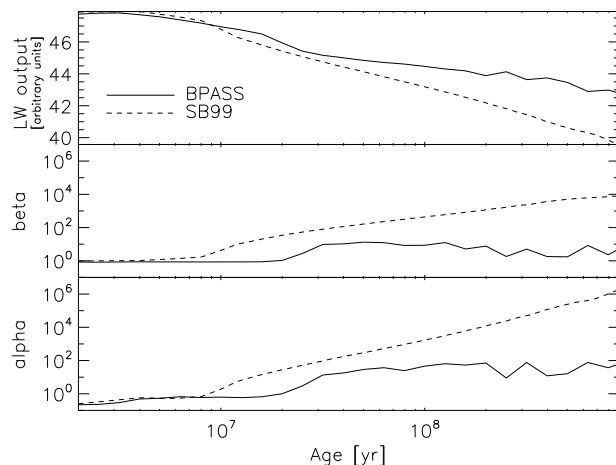
### 3 RESULTS

We first plot the LW output and rate parameters from BPASSv2 and SB99 models in the top panel of Fig. 2. As expected, the LW output of BPASSv2 is higher than that of SB99 at ages  $> 10$  Myr. Considering this fact alone, one would expect the  $J_{\text{crit}}$  from binary populations to be lower than the one from single stellar populations. However, the rate parameters,  $\beta$  (middle panel) and  $\alpha$  (bottom panel), for BPASSv2 are consistently lower than the ones produced by SB99 at all ages. This hints towards a more complicated interplay of the rates and the LW output leading to the need for a more in depth analysis of  $J_{\text{crit}}$ .

In Fig. 3, we compare the results of our analysis from the SB99 SEDs (top row) vs. BPASSv2 SEDs (bottom row). On the left we show the region in the  $M_*$ -age parameter space in which DCBH formation is permitted (grey), where the labelled contours indicate various different values of  $J_{\text{LW}}$ . The figure is split in top, middle and bottom panels corresponding to separations of 5, 12 and 20 kpc. In the right panels, we show the distribution of  $J_{\text{crit}}$  obtained by lowering the  $J_{\text{LW}}$  in the grey regions of the left panel, till a minimum value of  $k_{\text{di}}$  that satisfies Eq. 3 is obtained. The histograms are split by a stellar age of 400 Myr which roughly corresponds to the age of the Universe at  $z = 12$ , and the solid, dotted and dashed lines correspond to a separation of 5, 12 and 20 kpc respectively.

We find that the BPASS models produce systematically higher values of  $J_{\text{LW}}$  for any given combination of  $M_*$  and age, particularly when  $M_*$  and the age are both large. For example, a galaxy with an age,  $t_* = 10^{7.5}$  yr, a stellar mass  $M_* \sim 10^{9.5} M_\odot$  and a separation of 5 kpc from the atomic cooling halo of interest produces  $J_{\text{LW}} \sim 700$  with the BPASSv2 model, but only  $J_{\text{LW}} \sim 100$  with the SB99 model. This is because binary stellar populations yield more LW flux per stellar baryon especially at ages  $\gtrsim 10$  Myr (Fig. 2). Therefore, particularly at late times, one would expect them to be more effective in producing a higher  $J_{\text{LW}}$  value at a given distance than single stellar populations. From this one would naturally infer that binary populations are more efficient in causing DCBH formation in their vicinity. Despite this, we find that the  $J_{\text{crit}}$  is required for DCBH formation is higher from binaries than when we assume that all stars are single.

This apparently counterintuitive result is actually just a reflection of the fact that the value of  $J_{\text{crit}}$  required for DCBH formation depends on the whole of the SED. Although BPASSv2 has a



**Figure 2.** The LW output for  $M_* = 10^6 M_\odot$  (top), and the rate parameter for  $\text{H}_2$  photodissociation  $\beta$  (middle) and  $\text{H}^-$  photodetachment  $\alpha$  (bottom) as a function of time from BPASSv2 and SB99.

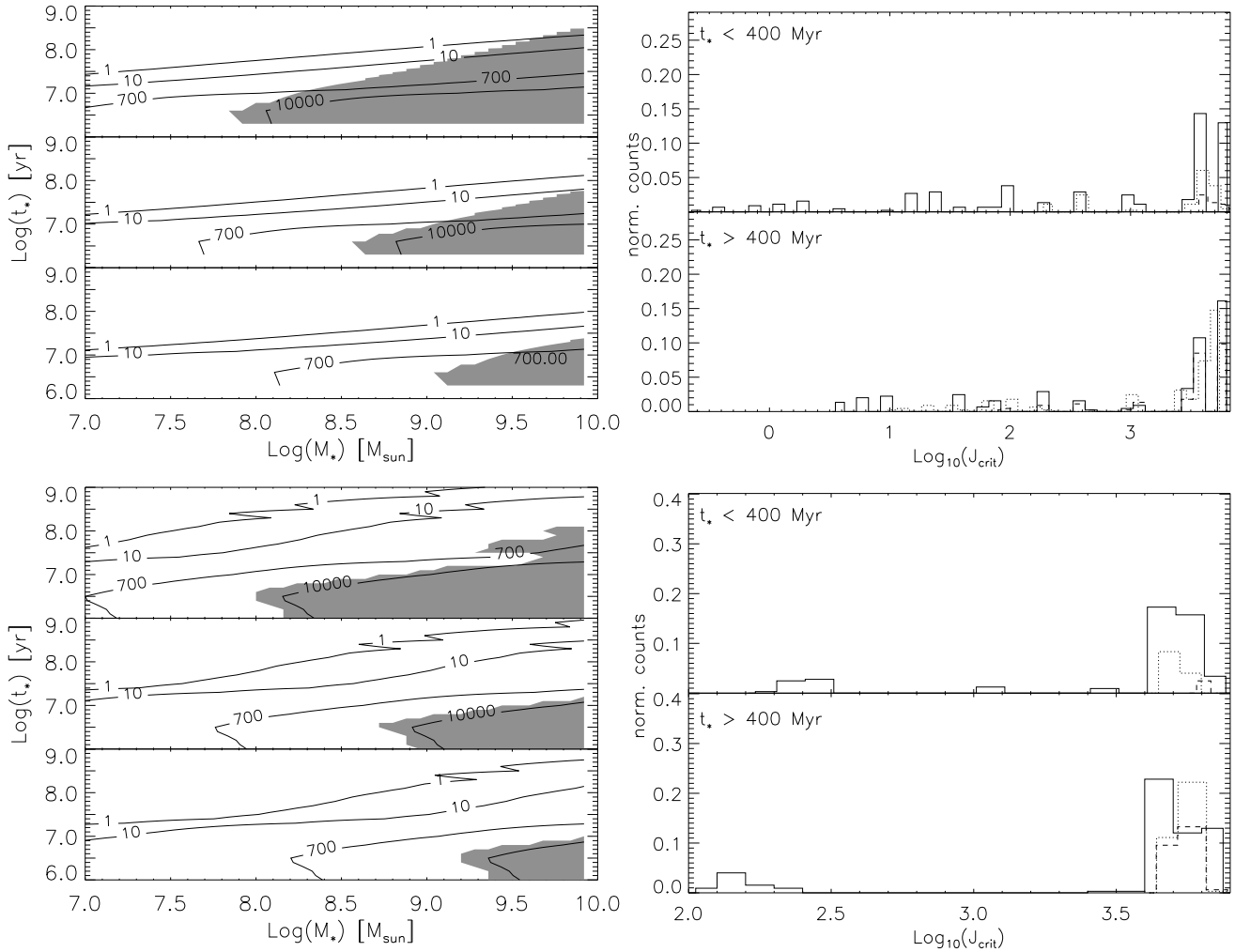
higher LW output, SB99 SEDs produce more lower energy photons and are thus much more effective at destroying  $\text{H}^-$ , as can be seen in Fig. 2 where the values of  $\alpha$  and  $\beta$  plateau for BPASSv2 but steadily rise for SB99 at stellar ages  $\gtrsim 10$  Myr. Consequently, with the SB99 SEDs, we require fewer LW photons in order to successfully suppress  $\text{H}_2$  formation, and hence obtain a smaller  $J_{\text{crit}}$ .

Further confirmation of this finding comes if we compare the distribution of  $J_{\text{crit}}$  in the right panels of Fig. 3. For the BPASSv2 SEDs, we find values in the range  $100 \lesssim J_{\text{crit}} \lesssim 3000$ , depending on the age of the stellar population, whereas for SB99, the same IMF yields a much wider distribution with  $0.1 \lesssim J_{\text{crit}} \lesssim 3000$ . For all three separations, we plot  $J_{\text{crit}}$  from the BPASS and SB99 models in Fig. 4. The curves are similar at ages  $< 10$  Myr, but at later times, the  $J_{\text{crit}}$  from binary populations is higher than the one required from single stellar populations. For example, at an age of 50 Myr,  $J_{\text{crit}} \sim 100$  for the BPASSv2 SEDs, while it is only  $\sim 10$  when derived using the SB99 SEDs. In fact, we see from the left panels of Fig. 3 that a galaxy with  $M_* \gtrsim 10^9$  and same age (50 Myrs) can easily have  $J_{\text{LW}} > J_{\text{crit}}$  when it is described by a SB99 SED, while for BPASSv2 SEDs  $J_{\text{LW}} < J_{\text{crit}}$  at this age for all masses.

These findings lead us to conclude

- (i)  $J_{\text{crit}}$  does not solely depend on the LW photon yield, but on the 0.76 eV photon yield as well
- (ii) The *distribution* of  $J_{\text{crit}}$  depends on whether binaries are included in a galaxy's SED. We find that, for a stellar population of a given age and mass, the  $J_{\text{crit}}$  is higher when binaries are considered.
- (iii) The *distribution* of  $J_{\text{crit}}$  is critically altered by the inclusion of older stellar populations. Our analysis shows that  $J_{\text{crit}}$  originating from older single stellar populations ( $> 10$  Myr) is much lower than the one from similarly aged binary stellar populations
- (iv) Formation of DCBHs must be understood in terms of a critical region in the  $k_{\text{de}}$ - $k_{\text{di}}$  parameter space (Eq. 3)

We note that point (i) is not a new result: it was already remarked upon by Sugimura et al. (2014) and in A16. However, our results here do help to emphasize the dependance of  $J_{\text{crit}}$  on the shape of the SED, which in turn depends on physical parameters such as the inclusion of binaries and older stellar populations.



**Figure 3.** Stellar populations that allow for DCBH formation, from SB99 shown on top (taken from the Appendix of A16), and BPASSv2 on the bottom. *Left:* Grey regions bound the  $M_*$  – Age parameter space for which the stellar populations produce an  $H_2$  photodissociation rate that at the location of the atomic cooling halo that satisfies Eq. 3. The top, middle and bottom panels are computed for an assumed separation of 5, 12 and 20 kpc between the atomic cooling halo and the irradiating source. The contours of  $J_{LW}$  at the respective distances are over-plotted in each of the panels. *Right:* Histograms of  $J_{crit}$  obtained by lowering the value of  $J_{LW}$  till Eq. 3 is still valid in the grey regions from the left panel. The solid, dotted and dashed lines correspond to the 5, 12 and 20 kpc separations respectively and the panels are split by stellar age of 400 Myr which roughly corresponds to the age of the Universe at  $z = 12$ .

#### 4 SUMMARY

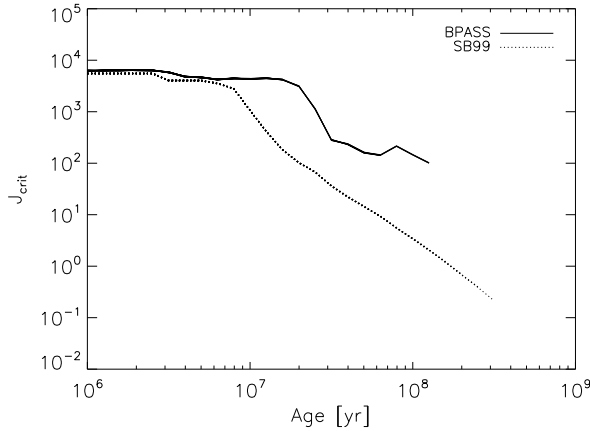
We study the LW flux requirement for DCBH formation from galaxies that have a stellar population that includes a significant binary fraction. We show that despite their high LW output, binary populations are in fact inefficient at causing DCBH in their vicinity when compared to single stellar populations, contrary to what one would naively expect. This can be attributed to the SEDs of binary populations that are systematically bluer than those of populations composed only of single stars, meaning that the light from them is much less effective at causing  $H^-$  photodetachment. The lower  $H^-$  photodetachment rates mean that higher  $H_2$  photodissociation rates are needed in order to bring about DCBH formation, and so the required values of  $J_{crit}$  are larger.

We still find a distribution in the values of the  $J_{crit}$  produced by binary populations, albeit narrower ( $J_{crit} \sim 300 - 3000$ ) than the one produced by single stellar populations ( $J_{crit} \sim 0.1 - 3000$ ). Furthermore the need for older single stellar populations becomes clear as they produce the lowest values of  $J_{crit}$  in both cases, due

to a higher  $k_{de}$ . This pushes the idea further that the formation of DCBHs must be understood in terms of the  $k_{de}-k_{di}$  parameter space (Eq. 3), and not in terms of a single flux value (also see A16).

#### ACKNOWLEDGEMENTS

BA would like to thank Laura Morselli for her useful comments on the manuscript, and Eric Pellegrini and Claes-Erik Rydberg for useful discussions. BA would like to acknowledge the funding from the European Research Council under the European Community's Seventh Framework Programme (FP7/2007-2013) via the ERC Advanced Grant STARLIGHT (project number 339177). Financial support for this work was provided by the Deutsche Forschungsgemeinschaft via SFB 881, "The Milky Way System" (sub-projects B1, B2 and B8) and SPP 1573, "Physics of the Interstellar Medium" (grant number GL 668/2-1).



**Figure 4.** Comparison of  $J_{\text{crit}}$  for BPASSv2 (solid) and SB99 (dotted), for all separations. This is an age distribution of the histograms, for the entire separation range, shown in the right panel of Fig. 3.

## REFERENCES

- Agarwal B., Dalla Vecchia C., Johnson J. L., Khochfar S., Paardekooper J.-P., 2014, *MNRAS*, 443, 648
- Agarwal B., Khochfar S., 2015, *MNRAS*, 446, 160
- Agarwal B., Khochfar S., Johnson J. L., Neistein E., Dalla Vecchia C., Livio M., 2012, *MNRAS*, 425, 2854
- Agarwal B., Smith B., Glover S. C. O., Natarajan P., Khochfar S., 2016, *MNRAS*, 459, 4209
- Begelman M. C., Volonteri M., Rees M. J., 2006, *MNRAS*, 370, 289
- Bromm V., Loeb A., 2003, *ApJ*, 596, 34
- Bruzual G., Charlot S., 2003, *MNRAS*, 344, 1000
- Chon S., Hirano S., Hosokawa T., Yoshida N., 2016, *arXiv.org*, [arXiv:1603.08923](https://arxiv.org/abs/1603.08923)
- Clark P. C., Glover S. C. O., Smith R. J., Greif T. H., Klessen R. S., Bromm V., 2011, *Science*, 331, 1040
- de Mink S. E., Langer N., Izzard R. G., Sana H., de Koter A., 2013, *ApJ*, 764, 166
- Dijkstra M., Ferrara A., Mesinger A., 2014, *MNRAS*, 442, 2036
- Eldridge J. J., Stanway E. R., 2016, *arXiv.org*, [arXiv:1602.03790](https://arxiv.org/abs/1602.03790)
- Ferrara A., Salvadori S., Yue B., Schleicher D., 2014, *MNRAS*, 443, 2410
- Greif T. H., Bromm V., Clark P. C., Glover S. C. O., Smith R. J., Klessen R. S., Yoshida N., Springel V., 2012, *MNRAS*, 424, 399
- Habouzit M., Volonteri M., Latif M., Dubois Y., Peirani S., 2016, *MNRAS*
- Koushiappas S. M., Bullock J. S., Dekel A., 2004, *MNRAS*, 354, 292
- Latif M. A., Schleicher D. R. G., Schmidt W., Niemeyer J. C., 2013, *MNRAS*, 436, 2989
- Leitherer C. et al., 1999, *ApJ*, 123, 3
- Lodato G., Natarajan P., 2006, *MNRAS*, 371, 1813
- Ma X., Hopkins P. F., Kasen D., Quataert E., Faucher-Giguere C.-A., Keres D., Murray N., Strom A., 2016, *MNRAS*, 459, 3614
- Machacek M. E., Bryan G. L., Abel T., 2001, *ApJ*, 548, 509
- Omukai K., 2001, *ApJ*, 546, 635
- O'Shea B. W., Norman M. L., 2008, *ApJ*, 673, 14
- Podsiadlowski P., Joss, P. C., Hsu J. J. L., 1992, *ApJ*, 391, 246
- Regan J. A., Haehnelt M. G., 2009, *MNRAS*, 393, 858
- Sana H. et al., 2012, *Science*, 337, 444
- Schleicher D. R. G., Palla F., Ferrara A., Galli D., Latif M., 2013,

*A&A*, 558, 59

Shang C., Bryan G. L., Haiman Z., 2010, *MNRAS*, 402, 1249

Stacy A., Bromm V., 2013, *MNRAS*, 433, 1094

Stanway E. R., Eldridge J. J., Becker G. D., 2016, *MNRAS*, 456, 485

Steidel C. C., Strom A. L., Pettini M., Rudie G. C., Reddy N. A., Trainor R. F., 2016, *ApJ*, 826, 159

Strom A. L., Steidel C. C., Rudie G. C., Trainor R. F., Pettini M., Reddy N. A., 2016, *arXiv.org*, [arXiv:1608.02587](https://arxiv.org/abs/1608.02587)

Sugimura K., Omukai K., Inoue A. K., 2014, *MNRAS*, 445, 544

Van Borm C., Spaans M., 2013, *A&A*, 553, L9

Volonteri M., Rees M. J., 2005, *ApJ*, 633, 624

Wofford A. et al., 2016, *MNRAS*, 457, 4296

Wolcott-Green J., Haiman Z., 2012, *MNRAS: Letters*, 425, L51

Zackrisson E., Rydberg C.-E., Schaerer D., Östlin G., Tuli M., 2011, *ApJ*, 740, 13